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AUTHOR(S) W. E. Fox
C. E. Cummings
R. F. Davidson
J. V. Parker

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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W. E. Fox, C. E. Cummings
R. F. Davidson, J. V. Parker
Los Alamos National Laboratory
Los Alamos, NM 87545

Summary

The hypervelocity experiment (HYVAX) railgun (Fig. 1) is designed to produce projectile velocities greater than 15 km/s in a 13-m-long, round bore gun. The HYVAX gun incorporates a modular design enabling it to operate in either a distributed energy-storage mode or a single-stage mode. The gun is composed of seven 0.3-m-long power input modules and nine 1.2-m-long accelerating modules. The gun is designed for a 100-shot life. To accommodate this, the bore may be enlarged from an initial diameter of 10.8 mm to a final diameter of 12.7 mm. This will allow the bore to be refinished several times during the life of the gun. To minimize mechanical and arc damage to the gun between bore refinishing operations, the gun will incorporate a low pressure helium projectile injector. Projectiles will be injected under vacuum at 350 m/s. The gun will be operated at a peak current and voltage of 600 kA and 6 kV respectively. The gun will undergo three phases of testing. The first phase will be the characterization of the gun's performance using a 3.0-m-long section of the gun comprising two power modules and two accelerating modules. This testing will be accomplished using two of the seven capacitor bank modules shown in Fig. 1. The second test phase will use a distributed power configuration and seven capacitor bank modules, as shown in Fig. 1, to demonstrate a velocity of 15 km/s with a 1-g projectile. The predicted performance of the gun for this test phase is illustrated in Fig. 2. In the third phase of testing we will use a magnetic flux compression generator (MFCG) to power the gun with a goal of demonstrating a velocity of 25 km/s.

Design Criteria

The design criteria for the HYVAX gun were extremely difficult to characterize because there was little knowledge available about the structural loading and response of railguns. We identified three key mechanical design considerations.

1. Plasma penetration between the rails and insulators needed to be minimized to prevent shorting.
2. Bore deformation under magnetic loading needed to be minimized to prevent projectile instabilities and bore damage.
3. Component stresses at expected loads needed to be minimized for multishot use.

These design issues are highly dependent on the magnetic and plasma pressure loading on the gun and on the duration of these loads.

To minimize the length of the gun, the "effective operating pressure" had to be as high as possible within the constraints of acceptable stresses in the gun components and its 100-shot lifetime. General experience with the structural characteristics of the materials used in constructing railguns (that is, epoxy composites and copper alloys) indicates that a maximum effective operating pressure of 0.7 GPa should be possible. Establishing this operating pressure as a goal provided a basis for the structural design criteria of the gun. The operating-pressure limit was also consistent with the pressure required to accelerate a 1-g projectile to 15-25 km/s in a gun of reasonable length.

Figure 3 describes the anticipated peak loading function on the gun when it is operated at maximum current in Phase II of the test program. At 7.5 m down the gun, with a projectile velocity of 19 km/s, the current peaks at 550 kA. This results in a symmetrical, localized plasma pressure loading of 0.5 GPa and a repulsive force between the rails of 3,000,000 N/m. Structural analysis revealed that because of the relatively short loading of the plasma pressure (~2 μ s), the dominant structural response was due to the repulsive force between the rails. This forces the bore into an oval shape and creates substantial cracks between the insulator and rail.

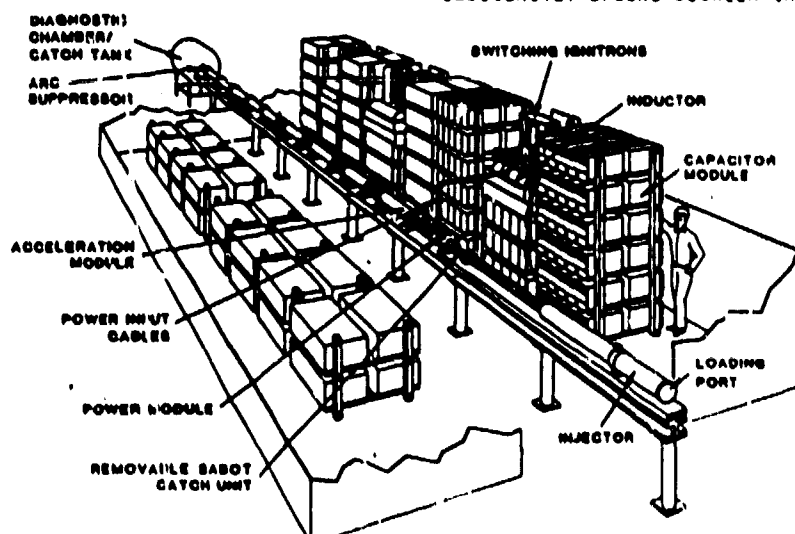


Fig. 1. Hypervelocity acceleration experiment - HYVAX.

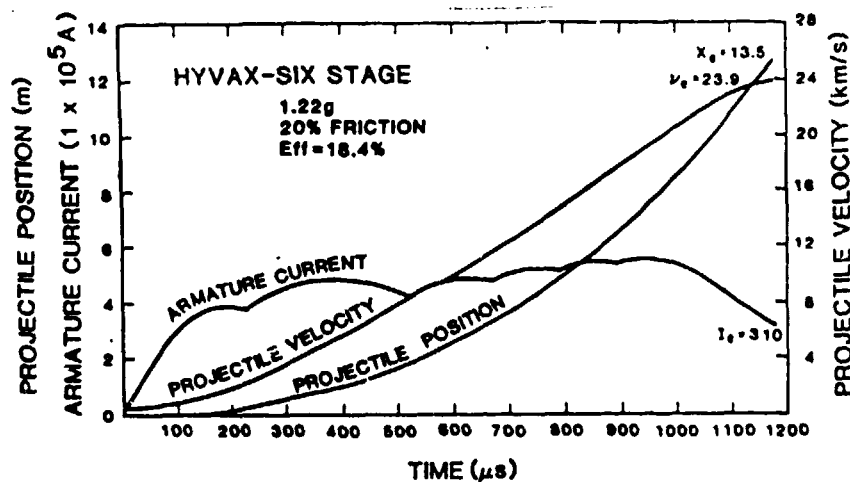


Fig. 2. Predicted Phase II test performance for HYVAX railgun.

unless it is resisted. To solve the problem, we used a high-modulus insulating material behind the rail; this will be addressed in greater detail later in this paper.

Even with a relatively high operating pressure, a gun length of over 13 m long is required to reach velocities in excess of 15 km/s. The difficulties in fabricating such a long gun combined with the requirement for distributed power input made it necessary for us to consider a modular gun. This approach offers the following advantages.

- a The ability to reconfigure the power input stations.
- w Simpler maintenance and repair.
- e Component sizes that are easier to handle.

The key problem associated with a modular gun is the requirement of an electrical and structural joint of high integrity. In the HYVAX gun, we addressed this problem by incorporating a lap joint in the rails. The lap joint is bolted together to provide an interface pressure of 1500 psi. To maintain a structural response at the lap joint consistent with the rest of the gun, we paid careful attention to the configuration of the insulators behind this lap joint. The power modules were made 0.3 m long, principally

to accommodate the three, 6-mm-diam power input studs and the accompanying insulation and structural support required to handle the 180 kA at which each module is rated.

Figure 4 is an illustration of the power module and its various component parts. On the basis of fabrication considerations, the accelerating modules were made 1.2 m long, and, with exception of the power input studs, resemble the power modules in cross section.

Mechanical Design

The HYVAX railgun is composed of two kidney-shaped rails adjoining two insulators (Fig. 5). The side wall insulator separates the rails and completes the bore of the gun. The rail backup insulators serve to insulate the rails from the outer shell and to resist rail movement during loading. These components are glued together and enclosed in a polyvinyl chloride tube to form a subassembly. The subassembly is then fit into a 1-in.-thick steel shell incorporating a tapered sleeve to eliminate assembly gaps and to slightly preload the subassembly. The steel shell provides structural support and serves as a vacuum vessel.

The complicated rail geometry results from considerations of structural integrity and heat transfer. The 45° shoulder on the rail limits relative displacement between the rail and the insulators. The flat shoulder on the bore side of the rail resists the rebound action of the rail and distributes this load over a larger area. The corners of the rail have a radius to decrease current densities and to keep temperatures below 350°C. The material chosen for the rails, a zirconium stabilized copper known as AMZIRC, maintains good mechanical properties at temperatures up to 400°C. Although the selected rail geometry decreases the inductance gradient of the gun, it was considered a necessary compromise to improve the structural integrity of the gun. The inductance gradient of the rail is expected to be 0.30 μH/m when installed in the steel shell.

A high-modulus, high-strength material was required for the sidewall and rail back-up insulators. A high-modulus material will prevent significant movement in the bore and store less mechanical energy during loading. This will result in low rebound loads. We selected an S-2 glass unidirectional composite with an epoxy-based matrix material. This composite is a good insulator and exhibits reasonable mechanical properties. A unidirectional composite can

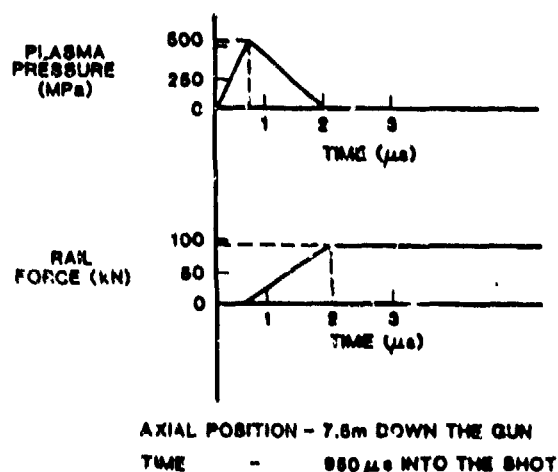


Fig. 3. Peak structural loading condition.

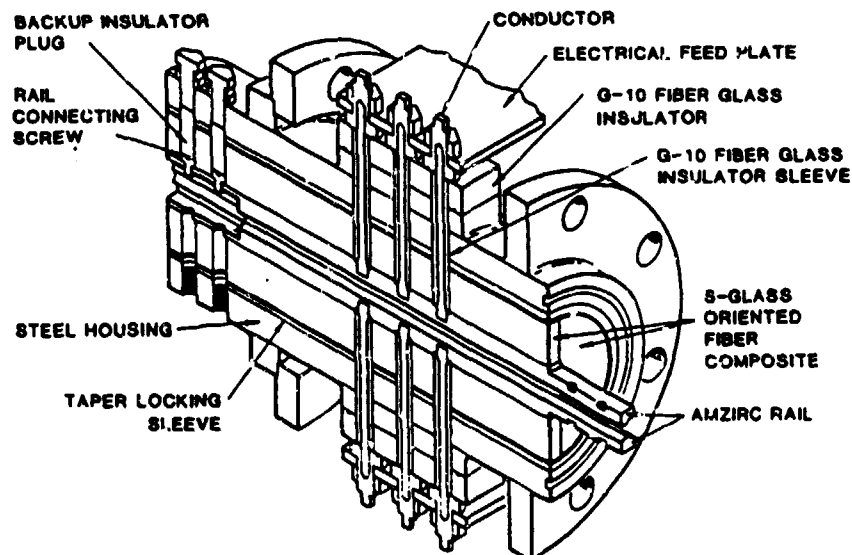


Fig. 4. HYVAX railgun power module.

be designed to exhibit highly orthotropic material properties by proper fiber orientation. This design was used in the insulating materials with 90% of the fibers oriented in the principal load direction and 10% oriented axially. The result is an elastic modulus of 38 GPa and a compressive and tensile strength of 0.76 GPa in the 90% fiber direction. Analysis reveals that these material properties will limit bore deflection to 0.5 mm at the peak loading condition shown in Fig. 3.

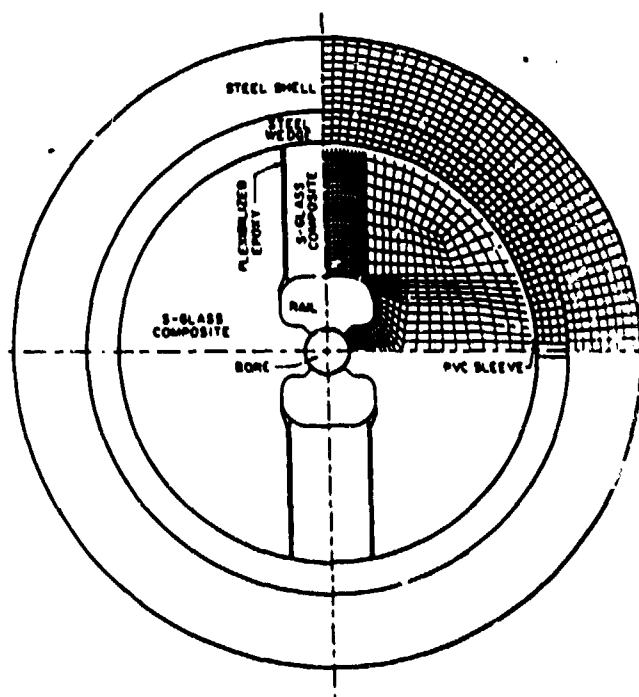


Fig. 5. HYVAX railgun cross section.

The steel shell, which is the principal confinement structure, reduces the inductance gradient slightly; but this effect was minimized by locating the shell several bore diameters from the back of the rail. The steel shell, made from AISI 1018, incorporates a tapered sleeve that assists in assembling and disassembling the module and provides a capability for preloading the subassembly. The steel shell also serves as a vacuum vessel. The gun will be operated at a pressure of 10^{-5} torr at either end of the gun. A pressure of 10^{-3} - 10^{-2} torr is expected in the center of the gun.

Assembly and Alignment

The key assembly issue is alignment of individual modules to a common axis. High-velocity light gas guns are typically aligned to tolerances of 100 $\mu\text{m/m}$. The individual module axis tolerance is expected to be 50 $\mu\text{m/m}$. Using conventional optical alignment equipment during assembly, we anticipate that the individual module tolerance will control the overall alignment accuracy to 100 $\mu\text{m/m}$. This is consistent with conventional gas-gun requirements and we believe it will be adequate.

Conclusion

The HYVAX railgun is a sophisticated, state-of-the-art electromagnetic launcher (EML), which should provide significant information on the performance of these devices. We expect to learn a great deal about rail joints, structural response, and materials. We will also gain considerable knowledge about the velocity capability of the EMLs.

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